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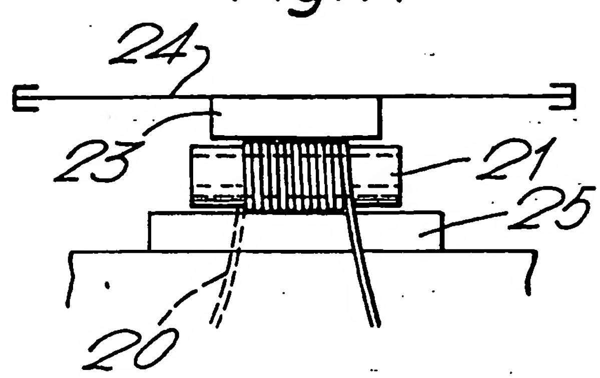
(54) **Acousto-optical fibre transducer**

(57) It is known that if an optical fibre is bent sharply the microbends thus produced cause a loss of light propogated in the fibre. Further, if the fibre with microbends is moved in accordance with a parameter to be sensed, then an optical fibre sensor results.

This invention relates to a number of forms of acousto-optical sensors in which the acoustical (or vibrational) waves to be sensed are caused to move a "microbended" fibre in such a way as to modulate the light in the fibre. In a preferred version the optical fibre (20) is wound as a coil on a hollow tube (21) of oval sections. The diaphragm (24) acts on the turns of the coil via a block-like element (23), the other side of the coil being mounted on an adjustable base (25).

Fig. 7.



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The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

Fig.1.

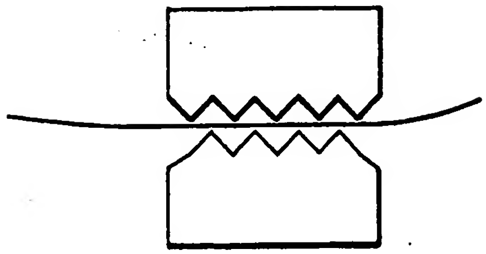


Fig.2.

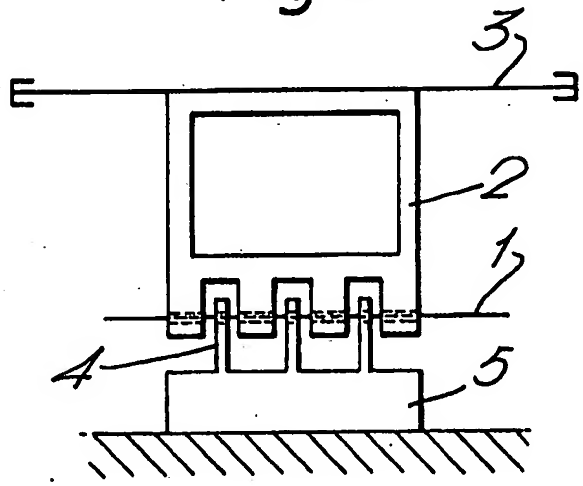


Fig.3.

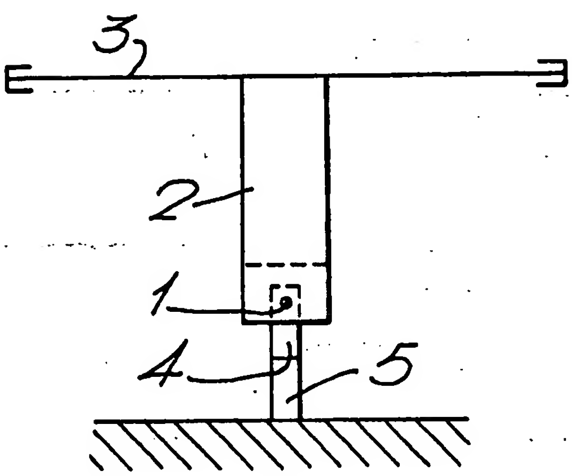


Fig.4.

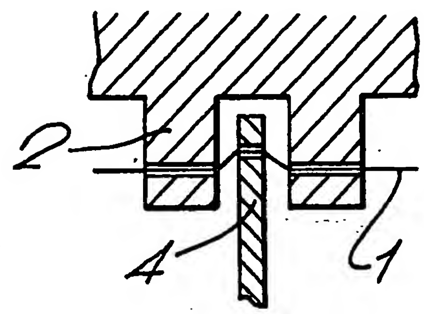


Fig.5.

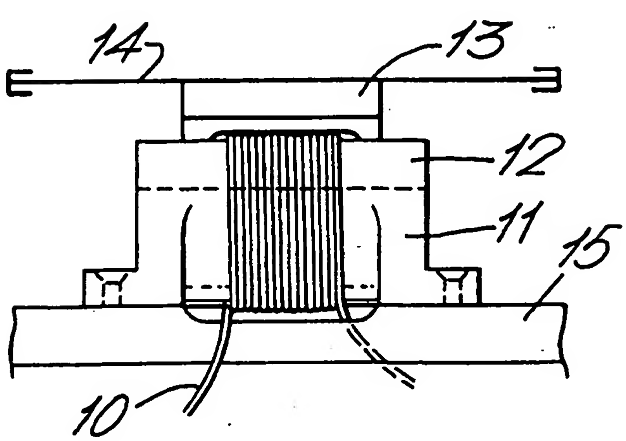


Fig.6.

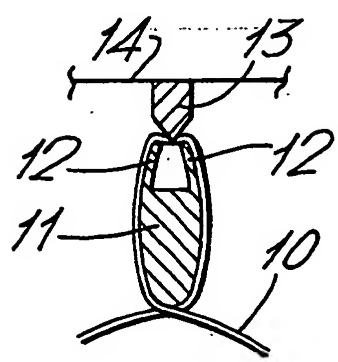


Fig. 7.

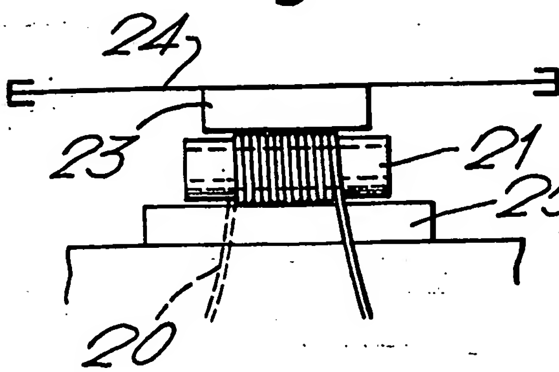


Fig. 8.

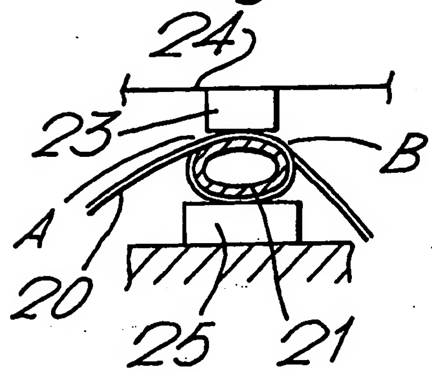


Fig. 9.

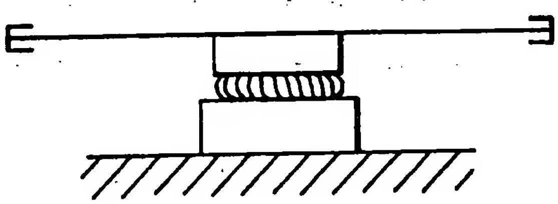


Fig. 10.

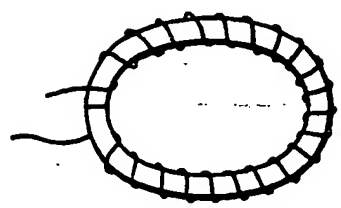


Fig. 11.

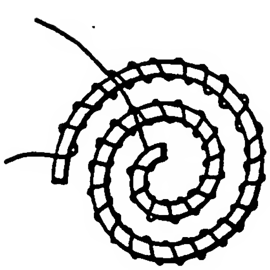
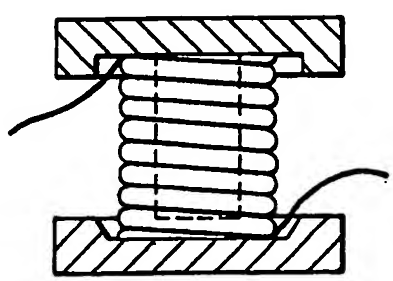


Fig. 12.



SPECIFICATION

Optical fibre transducer

This invention relates to acoustic-optical transducers, such as microphones, hydrophones and geophones.

It is known that when optical fibres are subjected to sharp bends, i.e. bends of small radius which are herein referred to as microbends, some of the light being conveyed by the fibre escapes therefrom. The amount of light lost in this way is approximately proportional to the inverse square of the radius over an operative range. A description of this effect, together with the application thereof as a pressure sensor, especially for very low (sub-audio) frequencies, will be found in a paper entitled "Fibre Optic Pressure Sensor" by J. N. Fields, C. K. Asawa, O. G. Ramer and M. K. Barnoski, published in the Journal of the Acoustic Society of America, Vol. 67 No. 3, March 1980, at pages 816-818.

It is an object of the invention to exploit this effect for the production of simple and economical acoustic-optical transducers.

According to the invention there is provided an acousto-optical transducer which includes at least one length of optical fibre through which light is propagated when the fibre is in use, a diaphragm or othermoving element which moves in response to incident acoustical waves or vibrations, which optical fibre is maintained in tension, and means whereby the fibre is subjected to a number of microbends and the said microbends are subjected to the influence of the diaphragm or other moving element so as to modulate the light in the fibre in accordance with the incident acoustic waves or vibrations.

Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is an explanatory diagram indicative of a known method of producing microbends in an optical fibre.

Figures 2, 3 and *4* are simplified diagams explanatory of the construction of a microphone which exploits the microbend effect.

Figures 5 and *6* are simplified diagrams of another microphone using the microbend effect.

Figures 7 and *8* are simplified diagraphs of a preferred form of microphone using the microbend effect.

Figures 9 and *10* are simplified diagrams of another form of microphone using the microbend effect.

Figure 11 is an alternative form of multi-microbend arrangement usable in the device of Figure 9.

Figure 12 is a hydrophone or geophone in which the microbend effect is used.

In the arrangement shown in Figure 1, an optical fibre is shown being subjected by sharp bending by the action of two serrated jaws, which trap the fibre such that relative movement of the fibre subjects the fibre to a number of sharp bends. A fibre so treated is usable as a sensor in the manner described in the above-mentioned paper.

Figures 2, 3 and 4 show a microphone in which an optical fibre 1 is maintained under tension, and is threaded through alternatively-opposed holes in a frame 2 carried by a diaphragm 3 and in upstanding legs 4 on an adjustable base 5. Hence the motion of the diaphragm in respnse to sound waves causes the fibre to undulate, which modulates light passing through it. This it does because the microbends thus set up and moved cause varying amounts of light to escape from the bends. Hence the light is modulated in a manner appropriate to the incident sound. Figure 4 is an enlarged "scrap" view showing the fibre-holes arrangement. With this arrangement fibre tension may cause some difficulty.

In Figurs 5 and 6 we see an arrangement in which the fibre 10 is closely wound on a moulded former 11, which former has flexible side members 12. Thus the turns of the fibre are subjected by tension due to the action on them of a narrow blade 13 attached to the diaphragm 14. The former 11 is mounted on an adjustable base 15. Such a construction allows many portions of the fibre to be undulated in response to the incident sound waves, thus making it considerably more sensitive than the device of Figures 2, 3 and 4.

The remaining arrangements are based on the principle that the fibre is close wound on a thin walled flexible tube which may be of rubber or a plastics material. Thus the degree of radial bending can be predetermind or adjusted by the initial flattening of the tube; the fibre is always correctly tensioned whatever the degree of tube flattening used. If necessary the wound fibre can be secured to the tube by an adhesive which is also flexible.

As will be seen later, in certain cases the tube is used as a mandrel, being removed after the fibre has been suitably wound.

Figure 7 and 8, show an optical fibre 20 close-wound on a tube 21 of oval cross-section. The turns of th coil of fibres thus produced are acted on by a pressure member 23 on the diaphragm 24, and the coil rests on an adjustable base 25. To increase the number of turns of fibre which are acted on by the pressure member 23, the tube can be bent round to form a circle, or the coil can be wound on a toroid as shown in Figure 10. Figure 9 shows a microphone using such a toroidal fibre coil.

Figure 11 shows how the effective number of turns can be increased beyond that attainable with Figure 10. In this case the coil former is a spiral tube, and increasing the number of turns of the spiral increases the number of microbends.

In yet another arrangement, see Figure 12, the tube on which the fibre is wound is formed into a helix, which is also closely wound, and can be of any desired length. The diaphragm, or moving element in the case of a hydrophone or geophone can be subjected to short or long amplitude waves, dependent on whether it is being subjected to sound waves, or much greater amplitudes as could occur if the transducer is beng used to measure machinery vibrations, or as a geophone.

In all the arrangements described above, the light input is provided by an LED or a laser from which light is launched into one end of the fibre. The

resultant modulated light emanates from the other end of the fibre and falls on a photo-diode or other suitable optical receiver such as a photo-transistor.

When very high sensitivity is needed, as in microphones or hydrophones, the wall thickness of the tube element can be extremely small and the material of that tube element very soft. Alternatively, as already mentioned, the optical fibre winding may be used without a tube. For instance, it can be coated with a thin adhesive skin while held on a rod-like mandrel which is removed after the adhesive has set on the coils. The adhesive should be kept clear of the minimum radius portions A and B in Figure 8, of the tube. The fibre used can be of the cladded or uncladded type.

The arrangements described above enable simple, low cost, and robust, yet highly sensitive microphones, hydrophones and geophones to be made. Unlike other proposals for optical fibre microphones, the arrangements described above do not need gaps or breaks in the fibres.

Fluid-filled or evacuated arrangements can be used, which enables variations to be made to the relative refractive indices of the fibres and their surrounds, so that sensitivity can be varied. Fibre failure can be catered for by winding the sensitive element with two or more fibres in parallel. Such multiple winding arrangement permits overall frequency characteristics to be widened or varied by using different light wavelengths for each of the separate windings.

Miniatured microphones can also be made using the above described techniques.

CLAIMS

1. An acousto-optical transducer which includes at least one length of optical fibre through which light is propagated when the fibre is in use, which optical fibre is maintained in tension, a diaphragm or other moving element which moves in response to incident acoustical waves or vibrations, and means whereby the fibre is subjected to a number of microbends and the said microbends are subjected to the influence of the diaphragm or other moving element so as to modulate the light in the fibre in accordance with the incident acoustic waves or vibrations.

2. A transducer as claimd in claim 1, in which the optical fibre which is in tension and is threaded through alternate holes of two sets of holes, one of which sets of holes is in a member driven by a diphragm while the other is in a stationary member.

3. A transducer as claimed in claim 1, in which the microbends are produced by wrapping the fibre about a supporting element having substantially parallel flexible wall-like portions, and in which the diaphragm carries a blade-like member which acts on the turns of the fibre in the vicinity of the wall like portions.

4. A transducer as claimed in claim 1, in which the optical fibre is wound on a tubular member of rubber or a rubber-like plastics material, and in which the diaphragm acts on the turns via a block-like member carried by the diaphragm.

5. A transducer as claimed in claim 1, in which the optical fibre is a self-supporting coil acted on by a block-like member on the diaphragm.

6. A transducer as claimed in claim 4 or 5, and in which the optical fibre coil is a circular or spiral or helical coil.

7. An acousto-optical transducer, substantially as described with reference to Figures 2 to 4, Figures 5 and 6, Figures 7 and 8, Figures 9 and 10, Figure 11 or Figure 12 of the accompanying drawings.

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D4 G7 P10 P3 R7 S4 S5
G2F 23F 25P1 28W CW
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None
(58) Field of search
G1A
H3A
(71) Applicants
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(54) Telecommunication systems

(57) A telecommunication system has a laser-energised multimode optical fibre 1. Data is input to the fibre by a series of modulators 4 each operating at a different subcarrier frequency. Optical radiation is detected by quadrant photodetector 3 which applies each of its outputs to respective channel sets. Each channel has a band pass filter 8 centred on a subcarrier frequency followed by a non-linear device 9. The signals from all the channels carrying the same subcarrier frequency are combined and the signals passed through band pass filters 11 centred on the second harmonic of the subcarrier frequency.

Each of the modulators 4 consists of a plate bonded by a piezoelectric transducer and a pressure plate between which a length of optical fibre is sandwiched. When the transducer is energised the acoustic energy produced applies asymmetric radial strain to the fibre which induces radial or transverse birefrigency, hence phase modulation of orthogonally polarised modes.

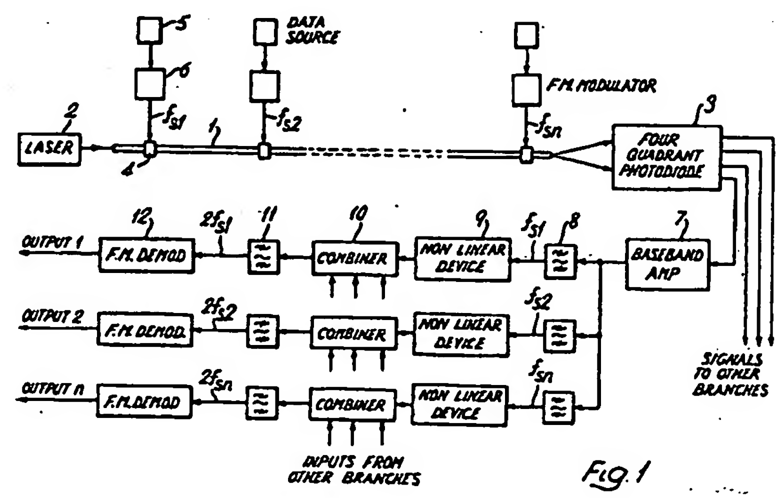

Fig. 1

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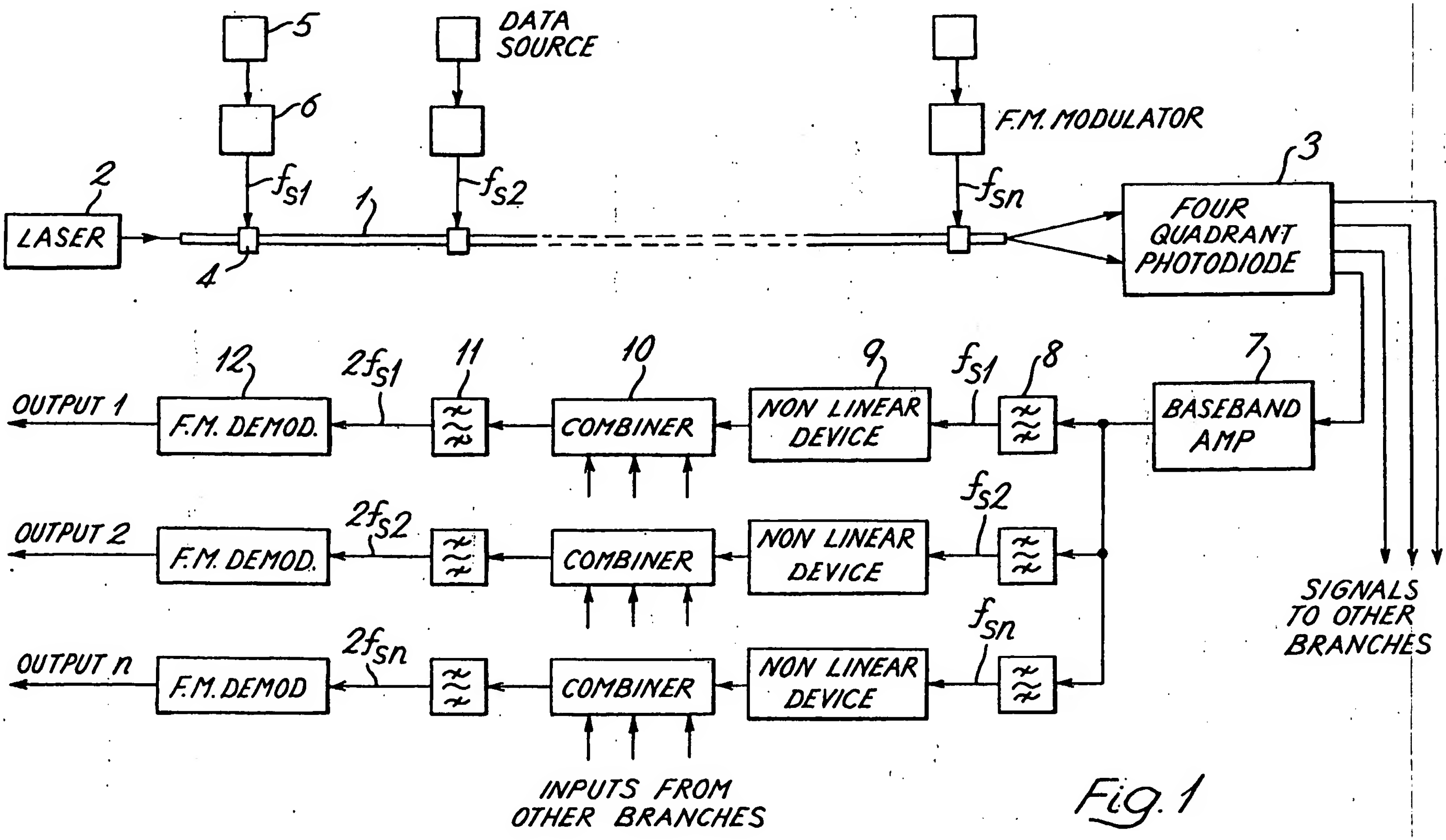
2
LASER
4
5
6
f_{s1}
1
DATA
SOURCE
f_{s2}
F.M. MODULATOR
f_{sn}
3
FOUR
QUADRANT
PHOTODIODE
7
BASEBAND
AMP
SIGNALS
TO OTHER
BRANCHES
8
f_{s1}
9
NON LINEAR
DEVICE
10
COMBINER
11
$2f_{s1}$
12
F.M. DEMOD.
OUTPUT 1
f_{s2}
NON LINEAR
DEVICE
COMBINER
$2f_{s2}$
F.M. DEMOD.
OUTPUT 2
f_{sn}
NON LINEAR
DEVICE
COMBINER
$2f_{sn}$
F.M. DEMOD
OUTPUT n
INPUTS FROM
OTHER BRANCHES

Fig. 1

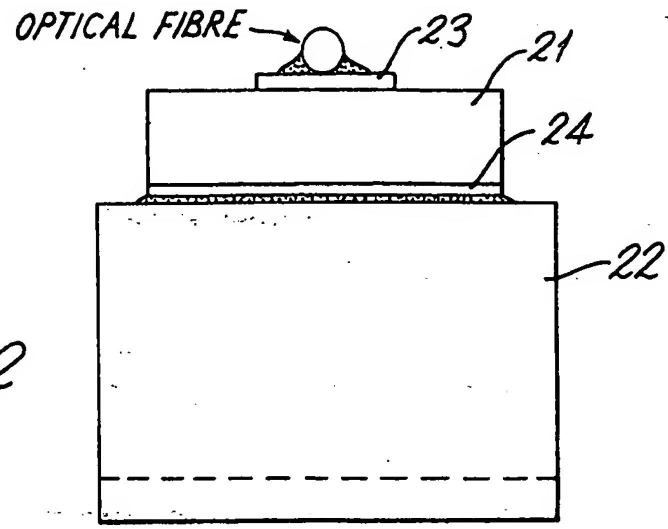

Fig. 2

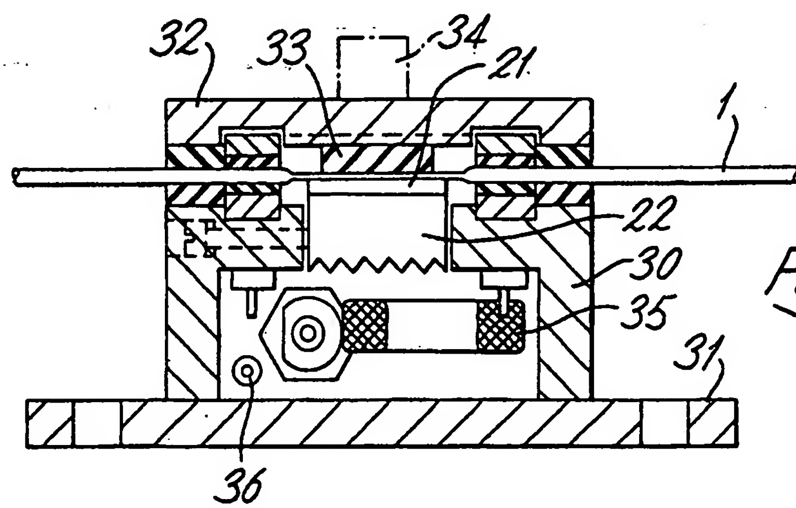

Fig. 3

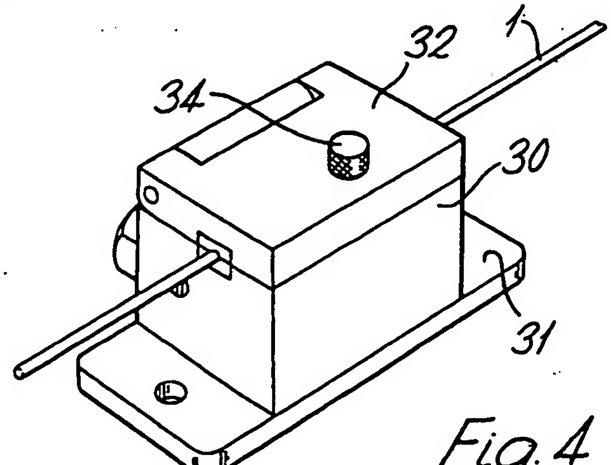

Fig. 4

SPECIFICATION
Telecommunications system

This invention relates to telecommunications systems and has particular application to telecommunications systems employing modulated optical signals.

According to the invention there is provided a telecommunications system comprising a multimode optical fibre highway, a source of coherent electromagnetic radiation of optical frequency at one end of the highway, a plurality of modulators spaced along the highway each comprising means for modulating an individual subcarrier signal with a data signal and means for periodically varying the optical path length of a short section of the highway with the modulated subcarrier signal, and demodulating means connected to the other end of the highway said demodulating means comprising photodetector means, a plurality of channels selective to individual ones of the subcarrier frequencies and each of said channels including a non-linear device, a filter responsive to an even harmonic of the subcarrier in that channel and an FM demodulator.

Preferably the said filter is responsive to the second harmonic of the subcarrier.

In carrying out the invention the photodetector means may be a multiple detector having two or more discrete areas each sensitive to different parts of the cross-section of the light beam from the fibre. Preferably four such areas or quadrants are used.

A separate set of channels is associated with the signals from each area of the photodetector and the channels of corresponding subcarriers from the different detector areas are combined before the second harmonic filters.

The source of radiation may be a gas laser or a solid state light source of adequate coherence.

In order that the invention may be more fully understood, reference will now be made to the accompanying drawing in which:

Figure 1 illustrates in block diagrammatic form an embodiment thereof,

Figure 2 illustrates a detail of a transducer assembly,

Figure 3 illustrates a transducer assembly in cross-section, and

Figure 4 is a perspective view of the transducer assembly of Figure 3.

Referring now to Figure 1 there is shown therein a length of optical fibre 1 functioning as a multimode fibre. A laser 2 is coupled to supply electromagnetic radiation of optical frequency to one end of fibre 1 while at its opposite end there is provided a four quadrant photodiode 3. Spaced along fibre 1 there is provided a plurality of modulators for enabling information to be impressed on the optical signal propagated along the fibre. These modulators are in the form of clip-on acoustic transducers 4. An example of such a transducer is described with reference to Figures 2, 3 and 4 and functions to phase modulate the optical carrier signal. The data to be carried by the highway is derived from sources such as source 5 and the data are applied to modulators 6 each modulating a separate subcarrier of frequency fs1, fs2 etc. Modulators 6 are preferably frequency or phase modulators.

At the far end of the optical highway the light from the fibre is directed on to the four quadrant photodiode 3. This device has four sensitive areas each covering approximately one quadrant of the cross-section of the beam directed thereon. The outputs from each of the quadrants of photodiode 3 are taken to separate sets of channels. One such set of channels is illustrated in the figure. It comprises a base band amplifier 7 which amplifies the entire spectrum of signals obtained from one of the quadrants and the output of amplifier 7 is then applied to individual channels of the set each of which commences with a band pass filter 8 centered on an individual one of the subcarrier frequencies. Thus the signal in each channel comprises an individual modulated subcarrier signal.

The signals in the channels are applied to non-linear circuits 9 which generate harmonics of the subcarrier and in particular the second harmonic thereof. The outputs of the non-linear circuits are then applied to combiner circuits 10 in which the signals from the corresponding channels of each set are combined together to form a single channel. The output of a combining circuit 10 is then applied to a further filter 11 which passes an even harmonic only of the subcarrier signal, for example the second harmonic as shown in Figure 1. These second harmonic signals are then demodulated in FM demodulators 12 the outputs of which constitute signals representing the input signals from the data source 5.

In operation of the system illustrated in Figure 1 the effect of the multimode propagation in the optical signal in fibre 1 will be to convert the phase modulation impressed on the optical carrier into amplitude (envelope) modulation. This resulting amplitude modulated signal will be directly detected in the quadrants of the photodiode without the need for a separate reference signal.

It can be shown that the signals recovered from the photodiode are bipolar in phase, that is to say that assuming negligible fibre dispersion there exists only two phases for the recovered subcarrier signals. This polarity reversal is random in nature so that if the signals from two or more quadrants are combined they are likely to cancel each other out in a random manner and would not enhance the signal available from a single photodiode. However in view of the bipolarity if the second harmonic of the subcarrier signals are taken then the resultant frequency doubled signals will all be in phase with each other.

Where multimode propagation is utilised the interaction between the mode causes fading and sentivity to movement of the fibre. However space diversity detection by the use of a sectioned photodiode eliminates much of the effect of such

interaction since the fading of signals will be uncorrelated between the separate quadrants of the photodiode.

An example of a suitable transducer assembly is shown in Figures 2, 3 and 4. Since the optical fibre highway functions by utilising differential phase modulation between modes to produce amplitude modulation, this effect is encouraged by the use of an acoustic transducer that applies asymmetric radial strain to the fibre. This induces transverse, or radial, birefringency and hence phase-modulates orthogonally polarised modes with different depths of modulations. Basically the optical fibre, which may have its plastic coating stripped over a short length, is clamped to a piezoelectric plate so as to produce strain in the fibre in a direction predominantly normal to the plate but not in a direction parallel to the plane of the plate.

A detail of the transducer assembly is shown in Figure 2. It comprises a piezo electric plate transducer 21 bonded to a small block 22 of metal or plastic which acts as a mount. The plate may be initially supplied with upper and lower electrodes 23 and 24 or else may have a lower electrode only and is then bonded to block 22 and then polished down to the required thickness for resonance on the mount after which the top electrode is applied. The mount itself forms the ground connection to the lower electrode of the piezoelectric plate and when a plastic mount is used a conducting layer is deposited on its surface. The mount also provides acoustic clamping of the transducer for bandwidth broadening purposes. In use the optical fibre 1 is clamped to the top of the piezoelectric plate 21. Fibre 1 may be bared but in general this is not necessary. A suitable grease for temporary coupling or epoxy resin for permanent coupling may be used between fibre 1 and plate 21. Mount 22 may be constructed of perspex or cast-iron and may have a tapered or serrated base for scattering any acoustic signals which are not sufficiently attenuated. The piezoelectric plate can be constructed of quartz or lithium niobate.

The complete transducer assembly as shown in cross-section in Figure 3 comprises a housing 30 secured to a mounting plate 31 and containing a toroidal ferrite matching transformer 35 supplied with the input signal, a tuning inductor 36 for electrical tuning of the piezoelectric transducer, the mount 22 and transducer 21 bonded thereto is secured in the top of the housing and the optical fibre 1 is laid above it. A hinged lid 32 is swung down above the fibre and a rubber pressure pad 33 is interposed. Lid 32 is held down by a clamping screw 34. The complete assembly is shown in perspective in Figure 4.

Since the modulation of the optical signals in the fibre is in response to an applied acoustic pressure wave, it is also possible to incorporate a single data input channel (at base-band) which does not employ a subcarrier oscillator. In this instance, a short length of optical fibre may operate as an acoustic sensor (this is a known property of optical fibres carrying coherent optical signals). The acoustic signals will produce corresponding phase modulation of the optical carrier which again appears as amplitude (envelope) modulation at the photodiode. Fading of the acoustically detected signal due to the multimode propagation in the optical fibre may again be reduced by combining the second harmonic of the signals received on separate sections of the photodiode.

CLAIMS

1. A telecommunications system comprising a multimode optical fibre highway, a source of coherent electromagnetic radiation of optical frequency at one end of the highway, a plurality of modulators spaced along the highway each comprising means for modulating an individual subcarrier signal with a data signal and means for periodically varying the optical path length of a short section of the highway with the modulated subcarrier signal, and demodulating means connected to the other end of the highway said demodulating means comprising photodetector means, a plurality of channels selective to individual ones of the subcarrier frequencies and each of said channels including a non-linear device, a filter responsive to an even harmonic of the subcarrier in that channel, and an FM demodulator.

2. The system as claimed in Claim 1 in which the said filter is responsive to the second harmoni of the subcarrier.

3. The system as claimed in Claim 1 or Claim 2 in which the photodetector means is a multiple detector having at least two discrete areas each sensitive to different parts of the cross section of the light beam from the fibre.

4. The system as claimed in Claim 3 in which the detector has four of the said areas each positioned in quadrant.

5. The system as claimed in Claim 3 or Claim 4 in which a separate set of channels is associated with the signals from each area of the photodetector and the channels of corresponding subcarriers from the different detector areas are combined before the filters.

6. The system as claimed in any one of the preceding claims in which said modulators each comprise transducers coupled to the optical fibre highway so as to phase modulate the optical signal.

7. The system as claimed in Claim 6 in which the said transducers are acoustically coupled to the highway.

8. The system as claimed in Claim 7 in which said transducers comprise clip-on devices which are attached to the highway without severing the optic fibres.

9. The system as claimed in Claim 7 or Claim 8 in which the transducers each have a piezoelectric element for applying strain to the optic fibres.

10. A telecommunication system substantially as described herein with reference to Figure 1 of the accompanying drawings.

11. A telecommunications system substantially as described herein with reference to Figure 1 and Figure 2 and Figure 3 and Figure 4 of the accompanying drawings.

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